FINAL REPORT

MODELING AND STATISTICAL ANALYSIS IN QUALITY ASSURANCE

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1. INTRODUCTION

Quality assurance methods play a vital role in any organization involved in procurement activities and logistics. The United States Navy has long been a leader in the use of analytical and statistical methods for dealing with problems in procurement and production. Major areas of quality assurance in which the Navy has significant involvement include acceptance sampling, process control, and engineering test design and evaluation.

Procurement activities involve the use of acceptance sampling methods to assure that each lot or batch of production is judged either unacceptable or acceptable with respect to important quality characteristics while maintaining known risks. However, even in organizations whose main role is procurement, other statistical methods are necessary. When a vendor cannot produce a satisfactory proportion of his process output within specifications, it is necessary for the procuring organization to review the vendor's process control system. This may lead to a modification of his present procedures, or in many cases to the development of a new system. Furthermore, during the design and development stages of new products such as weapon systems or other large, complex systems, a significant effort must be devoted to engineering test and evaluation to insure that quality of design and quality of conformance desired by the procuring organization will be met by the vendor in the final production stages. Because quality cannot be inspected into a product, quality assurance activities must span the spectrum of production, procurement, and logistics activities This involves the use of a variety of statistical and analytical methods.

The focus of this research project has been the development of methods for designing process control systems and developing techniques for analyzing engineering test data, such as regression and time series methods, as well as the application of sampling inspection and control techniques to various problems

in defense procurement. During the conduct of the research, numerous site visits have been made to navy installations at Crane, Indiana, the Naval Ship Research and Development Center, the Operational Test and Evaluation Force at Norfolk, Virginia, and several units of the Naval Facilities Engineering Command. These visits have involved discussions of research projects with scientific, technical, and management personnel, and have served to focus research on statistical methods and quality of assurance procedures that are of current and direct interest to the Navy.

The research activities have focused on three principal areas. The first of these is the development of new methods for designing process control procedures. The second research area has involved statistical modeling and analysis, concentrating principally on regression analysis and time series analysis. The third area has involved the use of acceptance sampling schemes specifically designed for auditing service contracts. Each of these research areas have led to a number of publications. The next three sections of this report summarize the work performed in these areas. The appendix contains a number of papers published by the principal investigator and his co-workers based on this research. These papers contain more comprehensive presentations of the research results.

2. STATISTICAL PROCESS CONTROLS

A major effort has been devoted to the development of new methods for designing statistical process control procedures. Of particular interest are methods that directly utilize economic criteria as opposed to consideration of statistical criteria only (the traditional approach). This work has resulted in six published papers and one text book. The first paper, "The Economic Design of Control Charts: A Review and Literature Study", appeared in the

Journal of Quality Technology in April, 1980. This paper surveys previous and current research efforts in the field, and provides a framework for subsequent research.

The second paper, "Probability Models for the Occurrence of Defects", appeared in Frontiers in Statistical Quality Control, edited by H.J. Lenz and others, published by Physica-Verlag, Wurzburg, Germany, in 1981. This paper deals with a sampling problem for defects in which the usual assumption of a Poisson model for the occurrence of defects is invalid. Alternative models are developed, and it is shown that inappropriate use of the Poisson model can have serious economic consequences. This phase of the research evolved directly from discussions with scientific personnel facing such a problem at the Naval Ship Research and Development Center. Subsequently, other work by the principal investigator which was not funded by the Navy, indicated that similar problems occur in the semi-conductor manufacturing field, where defects and faults on ships do not occur according to a Poisson process across the silicon wafer.

The third paper, "Economical Control Policies for a Single Cause System", appeared in AIIE Transactions in 1981. This work evaluated four types of process control procedures: $\bar{x}/R$ charts, p-charts, a never-inspect policy and a regular inspection policy with periodic reset of the process. A designed experiement was used to structure test problems for all four policies and general guidelines for selecting the type of policy to use in practice were developed. It was found that the optimal policy type depends primarily on the magnitude of the process shift, the relative cost of variables and attributes sampling, and the search time for the assignable cause.

The fourth paper, "Cost Based Acceptance Sampling Plans and Process Control Schemes", was presented at the AIIE Fall Technical Conference in December, 1984, and also appeared in the conference proceedings. The papers reviews and compares the major approaches to cost modeling in quality assurance. A multi-

criteria formulation of the problem is given that attempts to directly blend both economic and statistical objectives into a single model.

The fifth paper, "Economic Design of an $\bar{x}$ Control Chart" appeared in the January 1982 issue of the Journal of Quality Technology. This paper presents a computer program for the optimal economic design of the $\bar{x}$ chart and illustrates its use. The computer program incorporates an optimization algorithm developed by the principal investigator that has subsequently been used by most other researchers in this field. The lack of computer software for designing statistical process control schemes using economic criteria has long prevented their widespread use by quality professionals. This represents the first step in making such software more readily available.

The sixth paper, "Economic Design of $\bar{x}$ Control Charts for Two Manufacturing Process Models", extends analytical models developed by the principal investigator in his 1980 paper. This article describes two different manufacturing process models to which an $\bar{x}$ control chart can be applied. The first model assumes that the process continues an operation while searches for the assignable cause are made, and the second assumes that the process must be shut down during this search. Economic models of the control chart for these two manufacturing process models are developed, and the sensitivity of the control chart parameters to the choice of model is explored. It is shown that the choice of the proper manufacturing process model is critical because selection of an inappropriate process model may result in significant economic penalties.

Finally, two other publications from this area of research should be mentioned. The first of these is an invited presentation given by the principal investigator entitled "Economic Models in Statistical Process Control" at the Joint Statistical Meetings, 1984, in Philadelphia, Pennsylvania. This session was attended by over 100 professionals, and summarized much of the research activity supported by the Navy in the area of statistical process controls over the last ten years. The second publication by the principal investigator is the

textbook entitled Introduction to Statistical Quality Control, John Wiley & Sons, New York, 1985. This work is a modern, comprehensive treatment of statistical quality control. Chapter 9 in this book emphasizes modeling considerations and the economic aspects of statistical process controls, and is a direct outgrowth of the Navy-sponsored work in this area.

3. STATISTICAL MODELING AND ANALYSIS

Substantial research has been conducted on a variety of problems dealing with data analysis and modeling. This has led to six papers on various aspects of regression analysis and time series modeling, and one textbook.

The first paper, "Interior Analysis of the Observations in Multiple Linear Regression" appeared in the Journal of Quality Technology, July, 1980. Regression methods are used extensively in statistical modeling and quality assurance. For example, regression models often form the basis of a process control scheme. They may also help the analyst identify the set of critical variables requiring control. This paper shows how the disposition of the data points in the factor space can be identified, leading to the location of remote or high-leverage points, and to the location of clusters of points that form pseudo-replicates. The identification of pseudo-replicates allows an approximate lack-of-fit test to be performed. The paper contains a computer program for implementing the algorithm. This paper was one of the earliest published works on regression diagnostics for identifying high leverage data points.

The second paper, "Augmented Robust Estimators", appeared in the August, 1980 issue of Technometrics. This paper deals with combining robust estimation criteria with a class of biased estimators for the multiple regression model. This new family of estimators works particularly well for data sets exhibiting non-normal error and multicollinearity.

The third paper, "An Analysis of Constrained Robust Regression Estimators", appeared in the Naval Research Logistics Quarterly in 1984. This paper is a direct extension of the Technometrics paper cited above. The performance of the combined estimators developed in the Technometrics paper is studied empirically through simulation experiments structured according to factoral designs. With respect to a mean squared error criterion, the combined estimators are shown to be superior to ordinary least squares, pure biased estimators, and pure robust estimators when multicollinearity and nonnormality are present. The loss in efficiency for the combined estimators relative to least squares is small when these problems do not occur. The paper contains several guidelines for the use of these combined estimators in practice.

The fourth paper, "Modeling and Forecasting Time Series Using Transfer Function and Intervention Methods", was prepared by invitation of the editor of AIIE Transactions, and appeared in the December, 1980 issue. This is a technical report on the identification, estimation, and use of dynamic models for stochastic systems. These dynamic models can form the basis of feedback and feedforward schemes for process control. They are also useful in the analysis of engineering test data that appear in the form of a time series.

The fifth paper, "Problems of Nonnormality and Multicollinearity for Forecasting Methods Based on Least Squares", was prepared at the invitation of the editor of AIIE Transactions and appeared in the June, 1981 issue. This paper deals with the two most common problems in regression applications in engineering and physical science, nonnormality of the errors and illconditioned predictors. Various diagnostic procedures are proposed and illustrated along with several remedial measures, including a robust form of data smoothing.

The sixth paper entitled "Biased Estimation and Robust Regression" was prepared at the invitation of the American Society of Physicists in Medicine and was invited presentation at their summer conference in 1983. This paper

appeared in the proceedings of the conference. It summarizes recent developments in estimation techniques for linear models, with emphasis on biased estimation methods and robust fitting. The biased estimators reviewed include ridge regression, generalized ridge regression, principal components regression, and latent root regression. Classes of robust estimators discussed include M estimators, R and L estimators, and bounded influence estimation.

During 1984, the principal investigator published the second edition of his textbook entitled Design and Analysis of Experiments (John Wiley & Sons, New York, 1984). This book summarizes many recent developments in the statistical design of experiments and presents an engineering-oriented approach to the use of experiment design as a problem identification and analysis tool.

4. PROCEDURES FOR AUDIT SAMPLING

During the last two years of the research contract, the Naval Facilities Engineering Command has become interested in the use of statistical sampling procedures for monitoring service contracts. The principal investigator was asked to evaluate procedures currently in use by the Navy for this activity, and to suggest appropriate modifications if required. As a result of this research activity, a number of new approaches to audit sampling for monitoring and surveillance of service contracts were developed.

The primary approach involved the selection of a sample size and criteria for monitoring contractor performance so that if an unacceptable proportion of the contractor's work does not conform to Navy requirements, then there is strong statistical evidence for drawing this conclusion from the sample. Tables were developed so that Naval Facilities Engineering Command quality evaluators could select an appropriate sample size and an allowable number of defective performances, much as a military inspector would use conventional sampling

such as MILSTD 105D for the routine inspection of manufactured product. This procedure was tested in the field with good results and a modification of the Naval Facilities Engineering Command procedures for performing contract surveillance was prepared.

A technical presentation entitled "Sampling Procedures for Monitoring Service Contracts" was given as an invited paper by the principal investigator at Spring conference of the Operations Research Society of America, May, 1984, in San Francisco, California. During the development of the sampling procedures and the subsequent revision of the Naval Facilities Engineering Command guidelines, the principal investigator worked closely with Navy personnel to insure that the resulting systems and procedures would satisfy specific Navy objectives as to ease-of-use, statistical appropriateness of the surveillance methodology, and enforceability of any penalties for improperly performed service activities by Navy contractors.